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Continuously Injected Plasma Columns

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Abstract. Electron plasma columns continuously injected into a Malmberg-Penning trap display a rich evolution. Electrons emitted from an illuminated photocathode are trapped in the electrostatic well formed by the negatively biased photocathode and the trap end cylinder. Initially, the injections form cylinders of uniform density. As the density increases, the columns hollow in an attempt to match the potential profile of the equipotential cathode. The hollow columns are subject to the diocotron instability, and as the evolution becomes increasingly turbulent, the columns slowly expand to the trap wall. We present preliminary results and analysis of the trapping mechanism and the 2D dynamics of a continuously injected system.

INTRODUCTION

Malmberg-Penning traps consist of a series of collimated conducting cylinders, or gates, aligned along a strong magnetic field. Electron plasmas are confined in these traps by appropriately biasing the trap cylinders to form an axial electrostatic well. Radial confinement is provided by a strong magnetic field. Electrons are injected into the trap by momentarily grounding an “inject” gate near the cathode, and allowing electrons from the negatively biased cathode to enter the trap (Fig. 1). The plasma can be imaged by briefly grounding the “dump” gate. The image formed on the phosphor screen is recorded by a CCD camera. Typically, electrons are injected into a trap for only a short time; here we study this injection process and examine the columns formed by long-term injection. For these studies we used the Berkeley Photocathode trap [1], in which electrons are created by photoemission. The trap is otherwise similar to most other Malmberg-Penning traps, and employs a magnetic field of 3T.

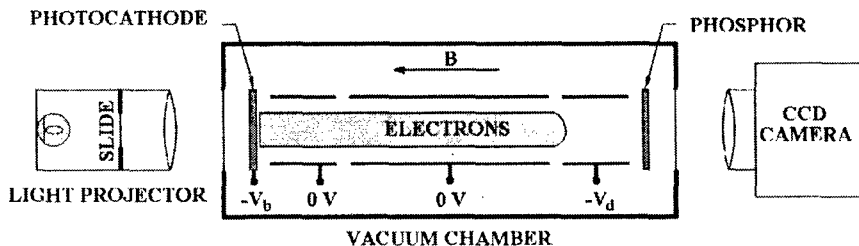


FIGURE 1. Schematic of the experimental apparatus during injection phase. The inject gate is on the left, and the dump gate on the right.

INJECT TIME DEPENDENT TRAPPING

Initially, electrons ejected from the cathode enter the trapping region, reflect off the dump gate, and are reabsorbed by the cathode. The electron density depends on the cathode current and the bounce time of an average electron. Calculations based on an average axial energy of 5eV and the measured electron emission current of $10\mu\text{A}$ ¹ from the photocathode give an electron density of $3\times 10^6\text{e}/\text{cm}^3$. Thus, there are approximately 2×10^7 electrons circulating in the 10cm long, 0.5 cm radius column. These electrons are trapped when the inject gate is biased negatively. Measurements (Fig. 2) find roughly similar numbers. However, as shown in the figure, the number of trapped electrons increases with time. At $100\mu\text{s}$ the number of trapped electrons is an order of magnitude greater than the number trapped initially.

Trapping Mechanism

Since the negatively biased photocathode forms a potential barrier, it can trap low energy electrons. Unperturbed electrons emitted from the photocathode have sufficient energy to traverse the trap and be reabsorbed by the photocathode. If, however, an electron loses axial energy within the trapping region (Fig. 3), it may not be able to return to the photocathode. This energy loss could result from a collision with a neutral gas atom, another electron, or from an electrostatic instability.

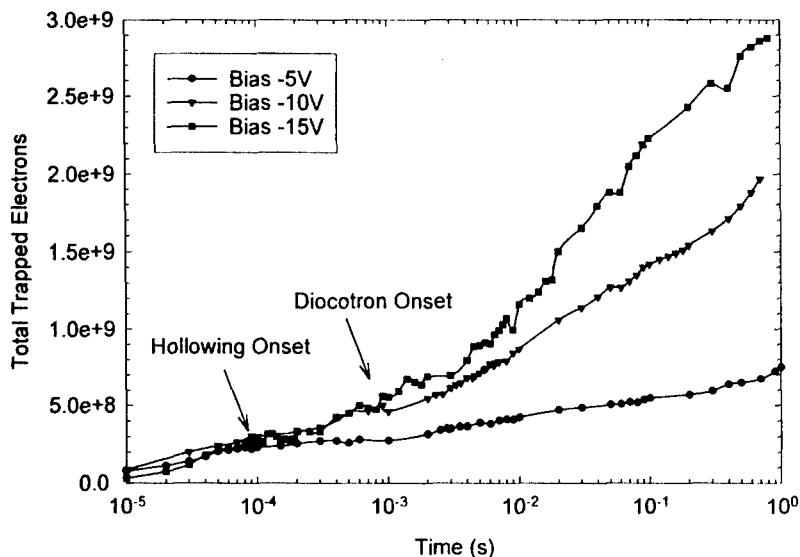


FIGURE 2. The total number of trapped electrons as a function of time for three values of the photocathode bias. The arrows indicate the approximate location of the onset of the column hollowing and diocotron stages of column evolution.

¹ Initially, the cathode operates in the emission limited regime.

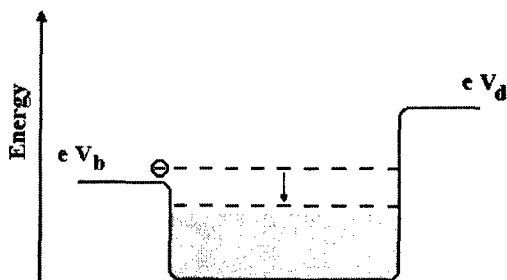


FIGURE 3. An electron may become trapped between the photocathode (V_b) and the dump gate (V_d) if it suffers an energy loss within the trapping region.

Residual gas collisions do not explain the observed trapping rates [2]. The residual gas in the trap is likely Cesium (Cs) at a chamber pressure of $<10^{-8}$ Torr ($n_{Cs}=3\times10^{14}\text{m}^{-3}$). Thus, using the Cs cross-section $\sigma = 5\times10^{-18}\text{m}^2$, the trapping rate is $2\times10^4\text{e}^-/\mu\text{s}$, two orders of magnitude smaller than the experimental trapping rate. Additionally, no change in the trapping rate is seen when the chamber pressure is raised to 10^{-6} Torr by turning the chamber pump off for several minutes.

Electron-electron collisions are also insufficient to explain the observed trapping rate. Assuming that an electron must scatter by 10° to become trapped and that the electron density is $1\times10^7\text{cm}^{-3}$, the calculated trapping rate is $1\times10^3\text{e}^-/\mu\text{s}$, three orders lower than the observed trapping rate. Note that only large angle scattering events are relevant, as multiple small angle collisions do not have time to operate in one transit.

EVOLUTION OF CONTINUOUSLY INJECTED PLASMAS

As the total charge increases, the system progresses through four stages [2]. In the first stage, the density of the column rises from approximately $10^6\text{e}^-/\text{cm}^3$ to approximately $10^7\text{e}^-/\text{cm}^3$ within the first $100\mu\text{s}$ of injection. The column profile changes from peaked at the center to flat-topped over this same time (Fig. 4a,b). For longer injection times, the column begins to hollow out as the space charge inhibits further injection into the center of the column. The central density decreases slightly while the density of the outer edge increases by a factor of three. By approximately 1ms , the column profile has become very sharp at the edge (Fig. 4c). The resulting column potential matches the cathode potential, in agreement with predictions by Driscoll and Malmberg [3]. The hollow ring configuration is unstable and undergoes a diocotron instability lasting approximately 10ms (Fig. 4d,e,f). In the final stage (beyond 100ms), the circumference of the original column emits streams of electrons that become wrapped into strong vortices orbiting in a diffuse background (Fig. 4g). The hollow column expands to several times its original size, eventually coming into contact with trap wall.

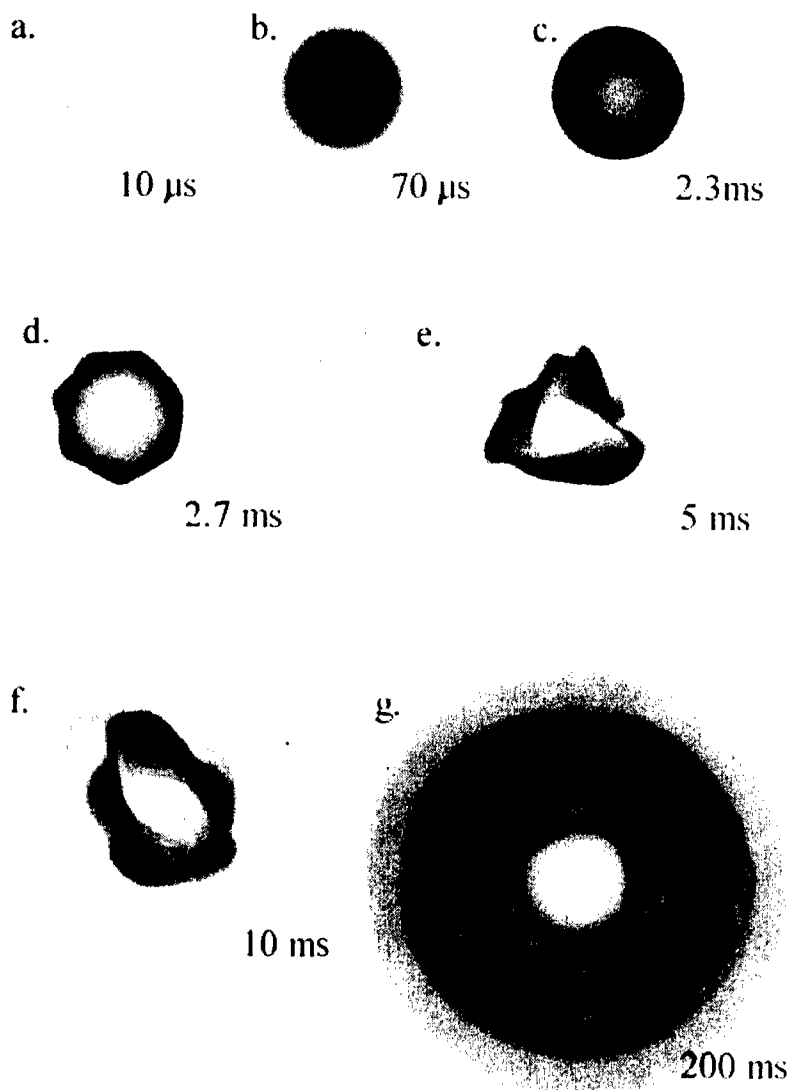
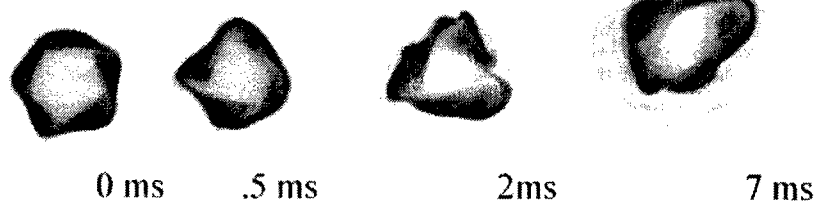


FIGURE 4. The evolution of a continuously injected plasma column demonstrating the four stages described in the text. The gray scales for the first 3 images (a,b,c) are the same to emphasize density differences as the column evolves to its hollow state. The edge of image (c) is highly saturated, masking the sharp profile along the circumference. The remaining images have been individually scaled for contrast. Color images may be found at <http://socrates.berkeley.edu/~fajans/>.

a.



b.

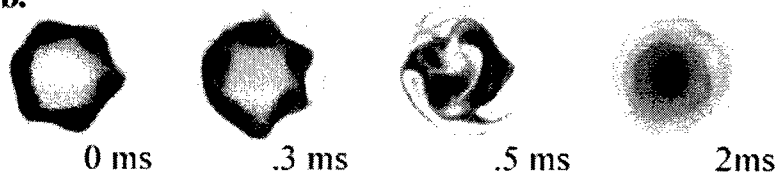


FIGURE 5. The progression of the diocotron instability a) in the presence of electron injection and b) without injection. Times shown are the time after the onset of the instability.

While the initial hollowing of continuously injected plasma columns is well understood, the evolution beyond the onset of the diocotron instability has not been studied previously. The diocotron instability itself changes in the presence of a background injection of electrons. The side-by-side progression sequences in Figure 5 show that the diocotron instability proceeds more slowly. This may be due to newly injected electrons smearing the diocotron density structures, thereby decreasing the self-consistent fields that drive the instability. The progression of the instability also expands the column significantly with the background electron injection. Normally, angular momentum conservation inhibits the expansion of the electron column. When electrons are continuously injected however, the new electrons change the angular momentum and the column can expand.

The final state of the system is a central ring surrounded by several strong vortices. Filaments often join the vortices and the central ring, and all these structures are immersed in a diffuse background (Fig. 6). New electrons enter the system primarily on the central ring. We postulate that this state results as follows: As shown in Figure 6a, the strong vortices deform the central ring. These deformations become filamented and extend radially away from the central ring, eventually winding around themselves. The small-scale structures in the resulting spirals smear out (Fig. 6b), and the spirals turn into vortices. Interactions with other vortices stretch, and eventually break the filaments connecting the vortices to the central ring. Newly formed vortices

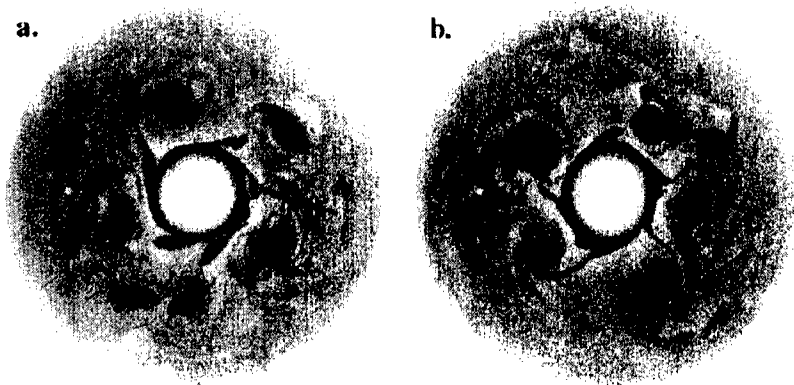


FIGURE 6. The long-term evolution of a continuously injected plasma column. The circumference of the original column is continuously supplied with electrons from the photocathode. Figure a) shows the early stages of filamentation (A) perturbation and (B) extension. Figure b) shows the later stages (C) capture and (D) spiraling. Images are representative of development at 200ms.

interact turbulently with the other vortices. Eventually viscosity destroys the vortex, and the vortex smears into the background. Before the vortex dissipates, it may come close enough to the central ring to cause a deformation, reinvigorating the cycle.

CONCLUSIONS

As shown by this work, the injection of plasma columns by a photocathode shows several well-defined stages of development. The theory for this development is not fully formed at this time, nor is the trapping mechanism understood. In the future, we hope to explore the trapping mechanism and its effect on electron temperature, density and 2D dynamics.

ACKNOWLEDGMENTS

Dr. Dan Durkin observed many of the phenomena recorded here and developed the trap itself. We thank Prof. Philip Marcus for discussions of 2D dynamics. This work is supported by NSF and ONR.

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